Expert insight into current research

News & views

Particle physics

Matter–antimatter symmetry violated

Silvia Pascoli & Jessica Turner

In a mirror world, antiparticles should behave in the same way as particles. But it emerges that leptons — neutrinos, electrons and their more exotic cousins — might not obey this expected pattern. **See p.339**

All visible matter in the Universe is made of fundamental building blocks, the elementary particles. The group of particles known as fermions consists of two types: quarks, which make up protons and neutrons; and leptons, namely, the electron, muon, tau particle and neutrino. For each elementary particle, there is an antiparticle that has the same properties but opposite charge. The best-known example is the antielectron, or positron. It was long thought that antiparticles would behave in the same way as particles in a mirror world made of antimatter, but since the 1960s we have known that quarks and antiquarks break this particle–antiparticle mirror symmetry[1,2]. On page 339, the T2K Collaboration reports possible findings of violation of this symmetry by leptons[3].

Particle–antiparticle mirror symmetry is also known as charge-conjugation parity-reversal (CP) symmetry; it combines the charge symmetry between particles and their antiparticles with parity (the idea that physical laws should not change in an antimatter mirror world). Why is CP symmetry broken, and what are its consequences? This puzzling question lies at the core of our understanding of the laws of nature and the evolution of the Universe.

As suggested[4] by Andrei Sakharov in 1967, CP violation is one of the key ingredients needed to explain why there is a small excess of matter over antimatter in the Universe. This imbalance, at a level of a few particles per 10 billion photons[5], is ultimately responsible for the existence of Earth, planets, stars and ourselves: if there were equal amounts of matter and antimatter, they would have destroyed each other in the early Universe and annihilated into photons. No matter would have remained.

How did this tiny excess arise from an initial Universe that was perfectly symmetrical? The amount of CP violation observed in quarks is not enough to cause it[6], so scientists have looked at leptonic CP violation in a well-studied mechanism called leptogenesis[7]. In models introduced to explain the observed neutrino masses, hypothetical heavy partners to neutrinos would have been copiously present in the early Universe and subsequently decayed. In the presence of CP violation, these decays could have generated the observed matter–antimatter asymmetry.

The discovery of substantial leptonic CP violation would be groundbreaking. Its observation, together with evidence that a quantity known as lepton number has been violated (that is, not conserved), would provide strong circumstantial evidence for leptogenesis as the origin of the matter–antimatter imbalance[8,9].

Leptonic CP violation is elusive, but can be searched for using neutrinos. These fundamental particles are remarkably reluctant to interact with ordinary matter, making them very hard to detect. They are the least understood known particle. Despite this, they are ubiquitous: your average coffee mug contains around 100,000 of the 'cold' neutrinos that permeate the Universe, and many times more produced by the Sun.

Neutrinos come in three types (flavours), determined by their associated charged lepton, whether that is an electron, a muon or a tau particle. It was long thought that neutrinos were massless. However, the discovery of neutrino oscillations by the Super-Kamiokande experiment[10] in 1998, and by the Sudbury Neutrino Observatory[11] in 2002, proved that these particles do have mass.

Neutrino oscillation is the phenomenon whereby neutrinos change from one flavour to another as they travel[12]. It is a quantum-mechanical effect that arises because each neutrino flavour is effectively a mixture — a quantum superposition — of three states that have different masses. Importantly, the superposition state can change over time because the components evolve differently (Fig. 1). For example, a neutrino that was produced as purely muon-flavoured can become partly an electron neutrino.

Since their discovery, neutrino oscillations have been analysed in several experiments, but only in the past few years have tiny oscillations from muon neutrinos to electron neutrinos been observed[13,14]. The probability of this oscillation occurring is small, but it holds the key to leptonic CP violation: if CP symmetry is conserved, the oscillation

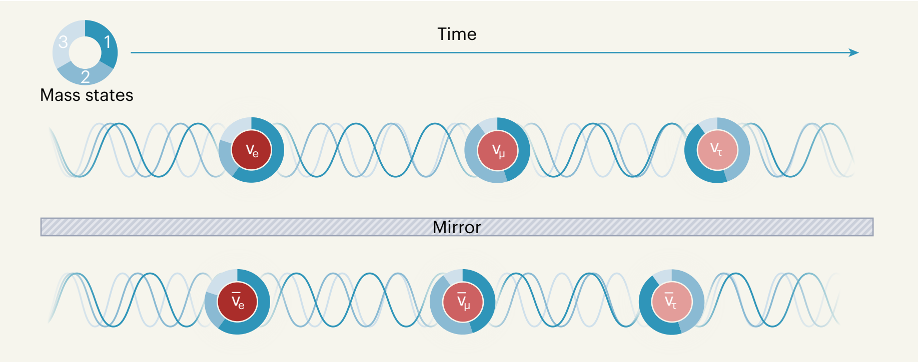

Figure 1 | Neutrinos through the looking glass. The elementary particles known as neutrinos have a curious ability to transform between three flavours (ν_e, ν_μ and ν_τ) over time, because the three components (mass states) of their make-up evolve differently; waves are simplified depictions of the contribution of each mass state to the neutrino. Each neutrino type has its own antineutrino (indicated by a bar). Symmetry rules imply that, in a mirror world made of antimatter, the antineutrinos should behave like neutrinos. But results from Japan's T2K experiment indicate that this symmetry might be broken[3]. The result could hint at how the Universe came to contain more matter than antimatter.

probability for muon-to-electron neutrino conversion would be the same as that for muon-to-electron antineutrino conversion. The T2K Collaboration has been able to study these oscillations with unprecedented precision, and has observed possible evidence of leptonic CP violation.

In the T2K experiment[15], a neutrino beam is generated at the Japan Proton Accelerator Research Complex in Tokai. Here, highly accelerated protons hit a dense graphite target, producing large quantities of particles known as pions and kaons. These particles decay, giving rise to a neutrino beam (or an antineutrino beam, depending on the conditions used), which is monitored by two detectors 280 metres away.

The neutrinos subsequently travel through Earth without being stopped, but some are detected by the underground detector at the Kamioka Observatory 295 km away, deep beneath Japan's Mount Ikeno. The detector consists of 50,000 tonnes of ultrapure water surrounded by a vast array of light sensors. When a neutrino interacts with a neutron in the water, it can produce a muon or an electron, depending on its flavour. The T2K experiment detects the muons and electrons and discriminates between them, thereby identifying the flavour of the impinging neutrino and measuring the oscillation probability of muon-to-electron neutrino conversion.

The T2K Collaboration analysed data collected between 2009 and 2018, in both neutrino and antineutrino mode. By combining this with input from other neutrino-oscillation experiments, the researchers have disentangled the dependence of the conversion probability on various parameters and thus provide evidence of CP violation. The results exclude CP conservation (that is, they suggest that CP violation has occurred) at a 95% confidence level, and show that the CP-violating parameter is likely to be large. These results could be the first indications of the origin of the matter–antimatter asymmetry in our Universe.

The measurement is undeniably exciting. But extraordinary claims need extraordinary evidence — a confidence level of more than 99.9999% will be needed to be certain that leptonic CP violation has occurred. This requires a more precise measurement of the oscillation probability, with more intense beams, larger detectors and better-understood experimental features.

The next generation of large-scale, multi-purpose neutrino experiments is preparing for the challenge. The T2HK experiment in Japan[16] is based on the same technology as T2K but will use the Hyper-Kamiokande detector, which will have ten times the mass of water and a more intense beam. Hyper-Kamiokande received official approval this February, and construction will start soon. And the Deep Underground Neutrino Experiment[17] (DUNE) will be based at the Sanford Lab in Lead, South Dakota; its technical-design report was published in February[18,19]. DUNE will use a different detector technology consisting of four modules filled with several thousand tonnes of liquid argon, to detect an intense beam of neutrinos produced 1,300 km away at Fermilab in Batavia, Illinois. Smaller prototypes tested at CERN, Europe's particle-physics lab near Geneva, Switzerland, have demonstrated the feasibility of the large-scale DUNE detector. T2HK and DUNE therefore provide complementary techniques and measurements. They will probably give us a definitive answer in the quest for CP violation in the next 15 years.

Silvia Pascoli is at the Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, UK. **Jessica Turner** is in the Theoretical Physics Department, Fermilab, Batavia, Illinois 60510, USA.
e-mail: silvia.pascoli@durham.ac.uk

1. Christenson, J. H., Cronin, J. W., Fitch, V. L. & Turlay, R. *Phys. Rev. Lett.* **13**, 138–140 (1964).
2. Gershon, T. & Nir, Y. in *Revew of Particle Physics* Ch. 13, 238–250; http://pdg.lbl.gov/2019/reviews/rpp2019-rev-cp-violation.pdf (Particle Data Group; 2018).
3. The T2K Collaboration. *Nature* **580**, 339–344 (2020).
4. Sakharov, A. D. *Sov. Phys. Usp.* **34**, 392–393 (1991).
5. Planck Collaboration. Preprint at https://arxiv.org/abs/1502.01589 (2015).
6. Gavela, M. B., Hernández, P., Orloff, J. & Pène, O. *Mod. Phys. Lett. A* **9**, 795–810 (1994).
7. Fukugita, M. & Yanagida, T. *Phys. Lett. B* **174**, 45–47 (1986).
8. Pascoli, S., Petcov, S. T. & Riotto, A. *Phys. Rev. D* **75**, 083511 (2007).
9. Hagedorn, C., Mohapatra, R. N., Molinaro, E., Nishi, C. C. & Petcov, S. T. *Int. J. Mod. Phys. A* **33**, 1842006 (2018).
10. Fukuda, Y. *et al. Phys. Rev. Lett.* **81**, 1562–1567 (1998).
11. Ahmad, Q. R. *et al. Phys. Rev. Lett.* **89**, 011301 (2002).
12. Pontecorvo, B. *Sov. Phys. JETP* **26**, 984–988 (1968).
13. Abe, K. *et al. Phys. Rev. Lett.* **112**, 061802 (2014).
14. Acero, M. A. *et al. Phys. Rev. Lett.* **123**, 151803 (2019).
15. Abe, K. *et al. Nucl. Instrum. Meth. Phys. Res. A* **659**, 106–135 (2011).
16. Hyper-Kamiokande Proto-Collaboration. Preprint at https://arxiv.org/abs/1805.04163 (2018).
17. Acciarri, R. *et al.* Preprint at https://arxiv.org/abs/1601.05471 (2016).
18. Abi, B. *et al.* Preprint at https://arxiv.org/abs/2002.02967 (2020).
19. Abi, B. *et al.* Preprint at https://arxiv.org/abs/2002.03005 (2020).

Geochemistry

Primordial nitrogen variations in the mantle

Rita Parai

A method for identifying atmospheric contamination of volcanic-gas samples reveals variations in the isotopic composition of nitrogen in the mantle, and provides a clearer view of the origins of this element in Earth's interior. **See p.367**

Earth's nitrogen-rich atmosphere contributes to the pleasant surface environment in which we live and breathe — but makes it very difficult to determine the nitrogen isotope composition of anything else. Pervasive atmospheric contamination of samples derived from Earth's mantle poses a formidable challenge to anyone investigating the origins and transport of volatile species, such as nitrogen and the noble gases, in the deep Earth. On page 367, Labidi *et al.*[1] report that they have used a 'clumped isotope' method to identify uncontaminated mantle nitrogen in volcanic-gas effusions and gases trapped in volcanic-rock samples. The relative abundances of isotopes in uncontaminated nitrogen vary among samples from different locations. The authors argue that these differences originate from Earth's formation and have survived approximately 4.5 billion years of mixing associated with mantle convection.

There are two stable nitrogen isotopes, ^{14}N and ^{15}N, and their relative abundances are expressed as δ^{15}N values — the parts per thousand deviation of the ^{15}N/^{14}N ratio from a standard value. The nitrogen isotopic compositions of mantle-derived samples can provide insight into a wide range of topics, from the mix of planetary building blocks that brought volatile species to Earth during its formation[2], to the transport of atmospheric nitrogen into the mantle through the sinking of tectonic plates over time[3].

Apart from the proportions of ^{14}N and ^{15}N in a sample, the way that isotopes are distributed between molecules also provides information. An isotopologue is a molecule that has a specific combination of isotopes of its constituent elements. For example, diatomic nitrogen molecules (N_2, which constitute about 78% of the atmosphere by volume) can incorporate either ^{14}N or ^{15}N, yielding three possible isotopologues: ^{14}N^{14}N, ^{14}N^{15}N and ^{15}N^{15}N. Because the vast majority of nitrogen is